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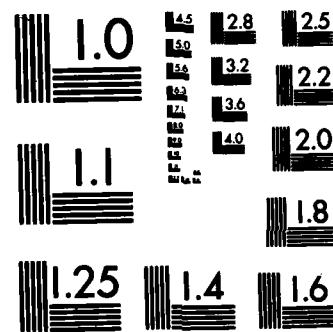
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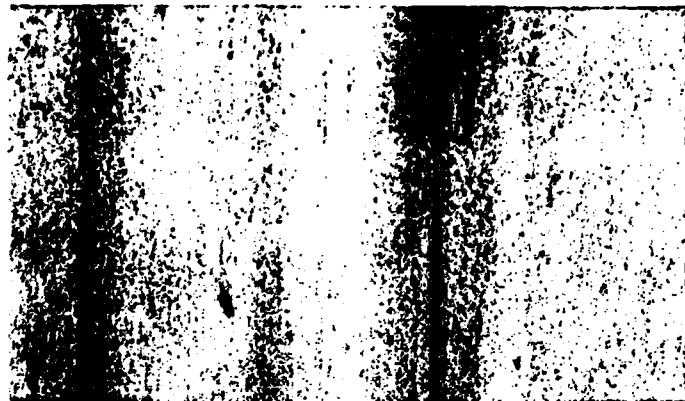
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TECHNICAL REPORT  
8035-1

THEORY OF HIGH SPEED DISPLACEMENT  
SHIPS WITH TRANSOM STERNs

by

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C. C. Hsu

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)	<p>A theory has been developed for high speed displacement ships. The theoretical treatment is based on treating the hull as finite in beam and draft but slender and the flow at the aft waterline being smooth and with a trailing wake. The trailing wake results in substantial residuary resistance at high speed for normal waterline shapes. Calculations are made for ships of highly variable parametric form and the results given. It seems that</p>	

20. the resistance, at high speed, may be greatly reduced through proper after-body design. A comparison of calculated results with the experimental results of NSRDC Series 64 shows good agreement and lends credence to the theory.

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INTRODUCTION

There is considerable interest in high speed displacement ships. These are characterized by high length-beam ratios, sharp bows, and flat sterns terminating in a transom. Such ships have been constructed for naval purposes, for example the German WWII Jaguar boats and their derivative the current Israeli missile boats, originally French built. All of these ships are reported to combine high surface speed with excellent seakeeping characteristics.

Systematic tests of conventional high speed forms were carried out at the David Taylor Model Basin and reported by H.Y.H. Yeh in 1964, Reference 1. These tests, comprising a series of 27 models, involved systematic variation in beam-draft ( $B/H = 2, 3, 4$ ) and block coefficient ( $C_B = 0.35, 0.45, 0.55$ ); the resulting length-beam ratios varied from about 8.5 to 18.0; the transoms were in general very full, their width being not too much smaller than the maximum beam.

The test results show a very significant residuary coefficient at the highest speed-length ratios, often exceeding 50 percent of the residuary pertaining at a speed length ratio ( $V/\sqrt{L}$ ) of 1.5, where wave resistance may be expected to be a maximum, see Figures 1A and 1B.

These results, taken together with the very fact of the wide transom stern evolution in design, raises some extraordinarily interesting questions concerning the hydrodynamics of these ships:

- 1) Since wave resistance is generally believed to decrease rapidly at high  $V/\sqrt{L}$  toward a value of zero, what exactly is the nature of the very large measured residuaries at high  $V/\sqrt{L}$ ? Spray? Other??

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2) Why are open sterns (transoms) desirable at high speeds?

After all, for submerged slender bodies, there is generally a positive form drag associated with open sterns.

Planing vessels have been rather extensively treated and rather good methods based on theory exist for the prediction of their performance, References 2 and 3; and the nature of their resistance (spray and "induced") is fairly well understood for slender surfaces, Reference 4. Strangely enough, however, there does not seem to exist any theory pertaining to the flow about high speed displacement ships, aside from preliminary theoretical considerations, such as those of Ogilvie, Reference 5. Nor is there a theory of transoms, except for the numerical calculations of Van Eseltine and Haussling, Reference 6. We certainly have not found answers to the two most interesting and important questions 1) and 2) above. Pertinent theory might not only answer these questions but provide methods for optimizing design, especially of the transom.

In view of this situation, the senior author initiated a theoretical study of slender high speed displacement ships under ONR Contract N00014-80-C-0669, with the results described below.

The theory is asymptotic to  $V/\sqrt{L} = \infty$  (no gravity), and assumes  $B/H = 0(2)$  and  $B/L \ll 1.0$ . All of these conditions seem realized in the high speed tests of Reference 1.

Most important, it is pointed out at the outset that the solution to the problem is not unique and that the physically realizeable solution involves in general, a "wake" flow behind the ship which carries energy and therefore results in resistance. This resistance is in general reduced by widening a suitable transom, and may in fact be anulled by a suitable transom with a width at the waterline equal to the ship's maximum beam.

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The theory is given analytical form and reduced finally to a boundary value problem in the cross flow plane, which must be solved for each cross section of the ship. A computer program is utilized to solve this problem and rather extensive calculations of resistance made for ships comprising Series 64, Reference 1. The results are excellent at the highest values of B/H and not bad for other values.

The results seem important; they suggest: a) that the greatest part of resistance of high speed displacement ships is due to the stern (we call it "stern-induced" resistance) and not to spray! b) that the "stern-induced" resistance may be eliminated through proper after-body design, and that the very existence of transoms lies in their ability to reduce such resistance; c) that the usual wave resistance problem is not completely posed, that the solution is not unique, and that the solution normally taken in existing theory, at least at high speeds, may result in physically unrealizable solutions.

Finally we point out that the theory may be applied to ships with yaw, and suggest that a sideforce linear in yaw results at high speed and can be calculated.

Directions for extension of the theory are pointed out.

THEORY

We are concerned here with slender ships ( $B/H = O(2)$ ;  $B/L \ll 1$ ) operating at "high" speeds ( $U_0^2/gL \gg 1$ ). We assume that the effects of viscosity are secondary. Consequently:

- 1) On the free surface, where  $p = \text{constant}$ , the speed  $q$  is everywhere the same and equal to the approach velocity,  $U_0$  far ahead of the ship. ( $q = \sqrt{U^2 + v^2 + w^2}$  where  $U = U_0 + u$ ,  $v$  and  $w$  are the  $(x, y, z)$  components of velocity, and where  $u, v, w = \phi_{x, y, z}$ ).
- 2)  $\nabla^2\phi = 0$  everywhere and  $\nabla^2\phi \approx \phi_{yy} + \phi_{zz} = 0$ ; therefore  $\phi = R[\psi(x; z + iy)]$ .  $q \approx U_0 + \phi_x$ .
- 3) The free surface may be taken in the  $(x-z)$  plane (i.e. at  $y \equiv 0$ ).
- 4) On the free surface,  $y = 0$ :  $\phi_x = 0$ , or  $\phi(x, 0, z) = \phi(z)$ .
- 5) The free surface consists of four separate regions, see Figure 2, a plan view. The entire free surface is  $S$  and the intersection of  $S$  and the hull is  $N$ , which defines the waterline shape. In  $S_0$ , the region outside the maximum beam:  $\phi = 0$ , since  $\phi(-\infty, 0, z) \equiv 0$ . In  $S_1$ , the forward shadow of the ship:  $\phi = 0$ , except in a narrow boundary near  $N$  which is the spray region  $S_s$ . In the narrow boundary layer  $S_s$  the flow on  $S_1$  (where  $w = 0$ ) adjusts itself very rapidly to the condition on  $N$  where

$$w \approx \pm \frac{U_0}{2} \frac{db}{dx};$$

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( $b(x)$  is the local beam of the waterplane). Physically, this adjustment is experienced as a thin spray sheet. In  $S_2$ , the rear shadow of the ship there are two distinct possibilities:

i)  $\phi = 0$

ii)  $\phi_z(x, z) = \phi_z(x_N; z)$ , where  $\phi_z(x_N; z) \approx U_o \frac{dz_N}{dx} = \pm \frac{1}{2} U_o \frac{db}{dx}$  [1]

The former possibility (i) would again require a narrow boundary layer along N wherein the lateral flow would adjust itself from its value on the hull to the value  $w = 0$  in the shadow. But the resulting solution requires (in this approximation) that flow detach from the hull with infinite vertical velocity and move downward to reach the water level downstream. In Figure 3 the free surface shape is shown schematically for a section of the bow and of the stern, according to both i) and ii) above. The "inverted spray" solution indicated by i) would lead to a narrow but high sheet of water between the hull and the wake surface everywhere along the stern and is not observed in practice, while the "smooth" flow indicated by ii) seems typical of observation. We therefore choose ii). This choice is equivalent to imposing the Kutta condition at the trailing edge of a slender wing or planing surface of waterline shape N.

6) As a result of ii), there exists in the entire rear shadow of the hull, prescribed values of  $w$  on the free water surface in  $S_2$ , see Figure 4.

7) On the hull surface:

$$\nabla (U_o x + \phi) \cdot \vec{n} = 0 \quad [2]$$

where  $\vec{n}$  is the outer normal (vector) at any point on the hull,

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and is given by:

$$\vec{n} = (n_x; n_y; n_z) = (\sin\beta; -\cos\beta \cos\alpha; \cos\beta \sin\alpha)$$

where  $\beta$  is the angle between the vector  $n_z + i n_y$  and  $n$ , and is given by (the subscript M refers to points on the hull):

$$\tan\beta = \cos\alpha \cdot \frac{\partial y_M}{\partial x}$$

or,

$$n_x = - [n_y \frac{\partial y_M}{\partial x} - n_z \frac{\partial z_M}{\partial x}] \quad [3]$$

Finally, assuming  $\phi_x/U_o \ll 1$ , Equation [2] yields:

$$\phi_y|_M = U_o \frac{\partial y_M}{\partial x}; \quad \phi_z|_M = U_o \frac{\partial z_M}{\partial x} \quad [4]$$

or, assuming in addition that  $\cos\beta \approx 1$ :

$$\phi_n = U_o [\cos\alpha \frac{\partial y_M}{\partial x} - \sin\alpha \frac{\partial z_M}{\partial x}] \quad [5]$$

8) Finally, in view of 1-7 above, the problem is reduced to a set of two dimensional potential problems in the cross flow plane as shown in Figure 5. Notice that the problem may be replaced by another which is equivalent, in which the hull beneath the water surface is augmented by its reciprocal above the surface, such that the equivalent body is source free in the far field, and may be represented by a dipole distribution; the flow is thus essentially wing-like. In this representation the surface  $S_2$  comprises a trailing vortex wake, and condition ii) of paragraph 5 is mathematically equivalent to the imposition

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of the trailing edge Kutta condition in the case of a slender wing, as noted earlier. The representation of the hull and its reciprocal involves additional vorticity. At the transom, the hull (plus reciprocal vorticity) plus free surface wake is shed into the ship's wake (plus its reciprocal) and manifests both the lift acting on the hull (vertical momentum in the wake) and the stern-induced resistance of the hull (kinetic energy in the cross flow).

9) The narrow spray region  $S_2$  corresponds to the leading edge region on a slender flat wing. In the latter case, the inability of the flow to follow the wing (go around the leading edge) leads to loss of leading edge suction and therefore to a resistance which is non-zero in the case of separation at the leading edge. The non-zero value of leading edge suction follows from the nature of the singularity at the leading edge of the flat wing

$$(\Psi' = w - iv \sim \frac{1}{\sqrt{\zeta}} , \text{ where } \zeta = z + iy)$$

In the case of a displacement ship with a vertical side at N, then it can be shown that  $\Psi' \sim \ln \zeta$  and that the waterline suction and therefore the spray resistance is zero in the present approximation. This surprising conclusion would seem to be borne out by our later comparison of predicted stern-induced resistance with experiments.

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SOLUTION

The flow about the ship, according to 2) above, can be described by a complex potential,

$$\Psi = \Psi(x; y, z) = \phi + i\psi$$

where  $\Psi$  is an analytical function of  $\zeta = z + iy$ . The complex velocity is:

$$\frac{d\Psi}{d\zeta} = \Psi' (x; y, z) = w - iv$$

and the velocity field is given by,

$$\nabla (U_0 x + \phi) = [U_0 + \phi_x; \phi_y; \phi_z] = [U_0 + \phi_x; -I(\Psi')' R(\Psi')] .$$

The complex velocity at each value of  $x$  may be represented in terms of a distribution of a suitable Green's function:

$$\begin{aligned} \Psi' (x; \zeta) &= \int \frac{Q(x; \zeta_1)}{2\pi} G(\zeta, \zeta_1) d\zeta_1 \\ M(x) + M^*(x) \end{aligned} \quad [6]$$

where  $Q(x; \zeta_1)$  represents the strength of the singularity distribution due to the presence of the ship equivalent boundary,  $M + M^*$ . A suitable Green's function in the present problem is the source:

$$G(\zeta, \zeta_1) = \frac{1}{\zeta - \zeta_1}$$

so that  $Q$  is the complex source strength.

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The contour  $M$  includes the submerged hull  $M_\ell$  and its reciprocal  $M_u$ , and  $M^*$  includes the vortex sheet on the free surface  $S_2$ , Figure 5, where  $\zeta_u = \bar{\zeta}_\ell$ , the overbar indicating the complex conjugate.

If  $Q_\ell$  is the source strength on  $M_\ell$ , and  $Q_u$  on  $M_u$ , then  $Q_u = \bar{Q}_\ell$  satisfies the boundary condition on  $S_0$  ( $w=0$ ). Equation [6] may thus be written:

$$\psi'(x; \zeta) = \frac{1}{2\pi} \int_{M_\ell} \left\{ \frac{Q d\zeta_1}{(\zeta - \zeta_1)} - \frac{\bar{Q} d\bar{\zeta}_1}{(\zeta - \bar{\zeta}_1)} \right\} + \frac{i}{2\pi} \int_{M^*} \frac{\gamma dz_1}{(\zeta - z_1)} \quad [7]$$

Since the integral on  $M_\ell$  contributes not at all to  $w$  on  $M^*$ , then on  $S_2$ :

$$\gamma(z_i) = -2w(z_1), \text{ the latter being prescribed by [1].}$$

Now, it is possible to show that,

$$-ie^{i\alpha} \psi' = \phi_n - i\phi_s \quad [8]$$

where  $s$  is the counterclockwise direction along the hull  $M_\ell$ .

Combining [7] and [8]:

$$R \left\{ -\frac{ie^{i\alpha}}{2\pi} \int_M \left\{ \frac{Q d\zeta_1}{(\zeta - \zeta_1)} - \frac{\bar{Q} d\bar{\zeta}_1}{(\zeta - \bar{\zeta}_1)} \right\} - \frac{e^{i\alpha}}{\pi} \int_{M^*} \frac{w(x; z_1) dz_1}{(\zeta - z_1)} \right\} = \phi_n(\zeta) \quad [9]$$

for all  $\zeta$  on  $M_\ell$ . Since  $\phi_n(\zeta)$  is known in terms of the hull shape, see Equation [5], this represents an integral equation for  $Q(x; \zeta)$ .

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The effects of the body shape and stern wake on  $S$  may be decoupled by seeking:

$$Q = m + i\gamma$$

where

$$R \left\{ -\frac{ie^{ia}}{2\pi} \int_{M_\ell} \left\{ \frac{md\zeta_1}{(\zeta-\zeta_1)} - \frac{md\bar{\zeta}_1}{(\zeta-\bar{\zeta}_1)} \right\} \right\} = \phi_n(\zeta) \quad [10]$$

for all  $\zeta$  on  $M_\ell$ .

$$R \left\{ \int_{M_\ell} \left\{ \frac{\gamma d\zeta_1}{(\zeta-\zeta_1)} + \frac{\gamma d\bar{\zeta}_1}{(\zeta-\bar{\zeta}_1)} \right\} - 2 \int_{M^*} \frac{w(x; z_1) dz_1}{(\zeta-z_1)} \right\} = 0$$

so that the body boundary conditions in the absence of shed vorticity are satisfied entirely by the hull source distribution,  $m$ ; and the effect of the shed vorticity is represented by an additional induced vorticity distribution,  $\gamma$ . These integral equations, of the Neumann type, can be solved numerically for  $Q(\zeta)$  on  $M_\ell$ .

To the slender body approximation, Bernoulli's equation becomes:

$$p = -\frac{1}{2}\rho(u^2 + v^2 + w^2) - \rho U_o \frac{\partial \phi}{\partial x} \approx -\rho U_o \frac{\partial \phi}{\partial x} \quad [11]$$

The incremental lift ( $dL_f$ ) and resistance ( $dD$ ) may be determined from knowledge of the pressure acting on a transverse slice:

$$\frac{dL_f}{dx} = \int_{M_\ell} p dz \approx -\rho U_o \int_{M_\ell} \frac{\partial \phi}{\partial x} dz \quad [12]$$

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$$\frac{dD}{dx} = - \int p n_x dz \approx \rho U_o \int \frac{\partial \phi}{\partial x} \frac{\partial \phi}{\partial n} dz \quad [13]$$

The total lift and resistance may then be approximated by:

$$L_f = \int_0^L \frac{dL_f}{dx} dx \approx -\rho U_o \int_{M_L} \phi dz \Big|_0^L \quad [14]$$

$$D = \int_0^L \frac{dD}{dx} dx \approx \rho U_o \int_{M_L} \phi \frac{\partial \phi}{\partial n} dz \Big|_0^L$$

[15]

$$-\rho U_o \int_0^L \int_{M_L} \phi \frac{\partial}{\partial x} \left( \frac{\partial \phi}{\partial n} \right) dz dx$$

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RESULTS

Extensive numerical studies have made for ships of the form:

$$y_m(x, z) = -h(x) \left[ 1 - \left( z / \frac{b}{2} \right)^2 \right]^{n_1} \quad [16]$$

with

$$b = b_o \left( \frac{x}{L} \right)^{n_2} \left( 1 - n_6 \frac{x}{L} \right)^{n_3} \quad [17]$$

$$h = h_o \left( \frac{x}{L} \right)^{n_4} \left( 1 - n_7 \frac{x}{L} \right)^{n_5} \quad [18]$$

The parameter  $n_1$  characterizes the fullness of the ships cross-section. Parameters  $n_2$ ,  $n_3$  and  $n_6$  govern the waterline profiles. Parameters  $n_4$ ,  $n_5$  and  $n_7$ , determine the draft variations. Calculations of both the lift and resistance have been made. However, in the following only the resistance results, which are of particular interest, will be discussed in some detail. The parameters  $n_1$ ,  $n_2$ ... etc are varied from a parent ship of the form:

$$n_1 = 0.4, n_2 = 1.0, n_3 = 0.5, n_4 = 0.25$$

$$n_5 = 0.5, n_6 = 0.87, n_7 = 0.9$$

$$\frac{L}{B} = 10, \frac{B}{H} = 4.0$$

where  $B$  and  $H$  are the maximum beam and draft of the ship. In these Figures, the resistance has been nondimensionalized by  $\frac{1}{2} \rho U_o^2 B^2$  and given by

$$C_D = \frac{D}{\frac{1}{2} \rho U_0^2 B^2} = C_{D_1} + C_{D_2} \quad [19]$$

in which  $C_{D_1}$  and  $C_{D_2}$  represent the contributions by the source (hull alone) and the vorticity (trailing wake caused) distributions respectively. The resistances due to source distributions ( $C_{D_1}$ ) are generally small, so that the resistance calculated is largely "stern induced", accompanying the trailing wake from the aft waterline.

The dependence of  $C_D$  on ship cross section fullness is shown in Figure 6. The values of  $C_D$  are small for ships of very full cross section and increase with increase in  $n_1$  until it reaches a maximum and then decrease with further increase in  $n_1$ . The effects of the parameters  $n_2$  and  $n_3$  (which determine the fullness of the waterline profile) on  $C_D$  are given in Figures 7 and 8. The resistances are smaller for finer bows (larger  $n_2$ ) and fuller sterns (smaller  $n_3$ ). The values of  $C_D$  with various parameter  $n_4$  and  $n_5$  which largely determine the draft variations near the bow and stern respectively are shown in Figure 9 and 10 and are smaller for higher rake bows (smaller  $n_4$ ) and sharper keel-rise sterns (larger  $n_5$ ). Although the effect is small over most of the range. In Figure 11, the strong variations of  $C_D$  with parameter  $n_6$  which dictates the location of maximum beam is given. The resistance is smaller for the location of maximal beam nearer to the stern. The effect of  $n_7$ , which determine the draft near stern, on  $C_D$  is shown in Figure 12. The resistance is smaller for shallower sterns (larger  $n_7$ ). The dependence of  $C_D$  on length-beam and beam-draft ratios is shown in Figures 13 and 14. The resistances are seen to decrease with increasing in length-beam and beam-draft ratio.

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The variations in resistances, except for parameters  $n_3$  and  $n_6$  are moderate for various parameter changes. The resistances are very sensitive to the variations in  $n_3$  and  $n_6$  as can be seen in Figure 8 and Figure 11. The resistance can be reduced substantially if the maximum beam can be moved more toward the stern (by decreasing  $n_6$ ). If the changes in beam near the stern can be made more gradual (by decreasing  $n_3$ ), the resistance can also be drastically reduced. These results seem to indicate that superior ship resistance characteristics at high speed may be achieved by proper shaping the waterline profiles around the stern.

These results are consistent with the fact that a waterline with maximum beam at the transom and with zero slope there ( $db/dx = 0$ ) will not create a trailing wake and will therefore be free of resistance  $C_{D_2}$ . In fact  $\phi_n \equiv 0$  at every point on the transom then  $C_{D_1} = 0$  too.

Numerical calculations for ship forms very similar to those of Series 64 high-speed displacement forms, Reference 1 are also made. The values of various parameters for these computations are given below:

$$n_2 = 0.975, n_3 = 0.525, n_4 = 0.25, n_6 = 0.865$$

$$\begin{aligned} n_1 &= 0.275, & n_5 &= 0.485, & n_7 &= 0.91 \\ n_1 &= 0.65, & n_5 &= 0.525, & n_7 &= 0.954 \end{aligned} \quad \left\{ \text{for } C_B \text{(block coefficient)} = \begin{cases} 0.55 \\ 0.45 \end{cases} \right.$$

These series of displacement hulls have the same waterline profiles but have different draft variations for different block coefficients. Comparisons between the calculations and the experimental residual resistance data (non-dimensionalized by  $\frac{1}{2}\rho U_0^2 B^2$ ) measured at the speed length of five by Yeh (Reference

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1) are shown in Figures 15a and 15b. The results are generally in good agreement, and especially for  $B/H = 3.0$  and  $4.0$ . Certainly the results would lend general confidence to both the theoretical developments and method of calculation.

EXTENSIONS

The theory presented here applies in the limit of very high speeds. A decrease in Froude number will involve both hydrostatic and wave sources of resistance. The hydrostatic effect on the transom is easily estimated. The waves must be the subject of additional theory, and an asymptotic theory (wavenumber small) suggests itself and could prove effective in the regime of high but finite speeds.

As noted in the introduction, a sideforce linear in yaw or sideslip develops due to the trailing wake and can be calculated.

The case of unsteady motions of the ship can be treated by the same kind of theory, possibly including motions in waves with forward speed (high speed limit).

And, finally, some of the startling results of the present paper deserve experimental verification. In that case, trim should also be calculated using the present results.

SUMMARY AND CONCLUSIONS

- 1) A theory has been developed and reduced to computation which applies to displacement ships in the limit of very high speeds.
- 2) Transom sterns may be treated.
- 3) The theoretical treatment is based on treating the hull as finite in beam and draft, but slender. It seems especially appropriate in the case of high speed ships which typically have large length/beam ratios.
- 4) In considering the consequences of the constant pressure condition on the free surface at high speeds it is revealed that two essentially different conditions can be imposed in the region aft of the maximum beam of the ship (in its shadow). One of these involves a thin sheet of water flowing rapidly down all along the aft waterline (inverted spray), and is discarded as physically unreal. The other involves a smooth flow at the aft waterline and a trailing wake (horizontal velocities on the free surface in the shadow). It seems physically realizable and corresponds to flows satisfying the Kutta condition at the trailing edge of slender wings.
- 5) Calculations are made for ships of a highly variable parametric form (seven constants) and the results given.
- 6) The trailing wake results in substantial residuary resistance at high speeds for normal waterline shapes. This is a completely new finding.
- 7) This residuary is typically reduced by widening the transom and is minimized by taking the maximum beam at the transom with sides there parallel to the flow direction. A shallow draft at the transom is also indicated.

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8) A comparison of calculated results with the experimental results of NSRDC Series 64 shows good agreement, especially at the larger values of B/H (3 and 4) and lends credence to the theory.

9) Extensions are indicated.

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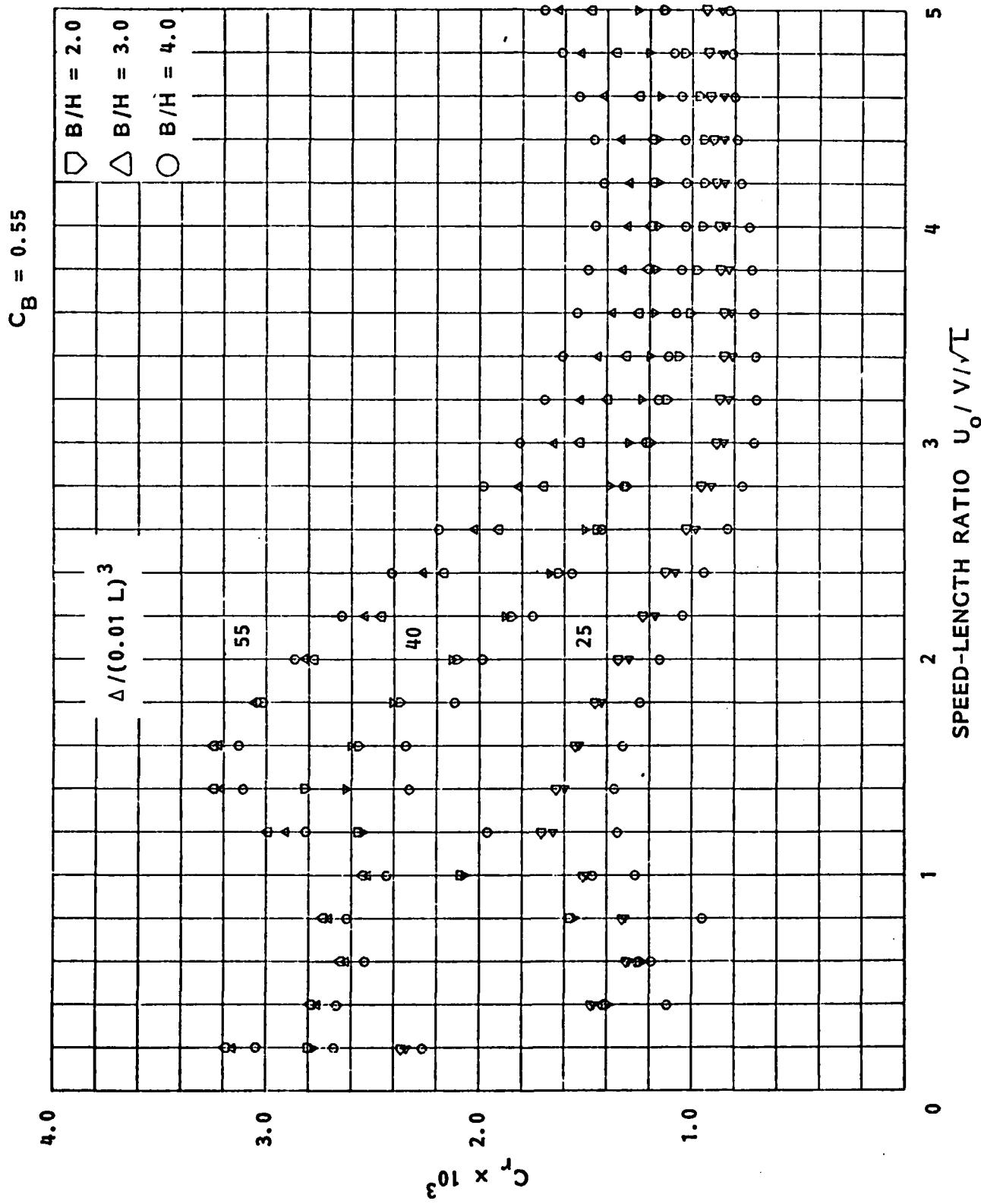


FIGURE 1A RESIDUARY-RESISTANCE COEFFICIENTS,  $C_r = R_r / 1/2 \rho S V^2$

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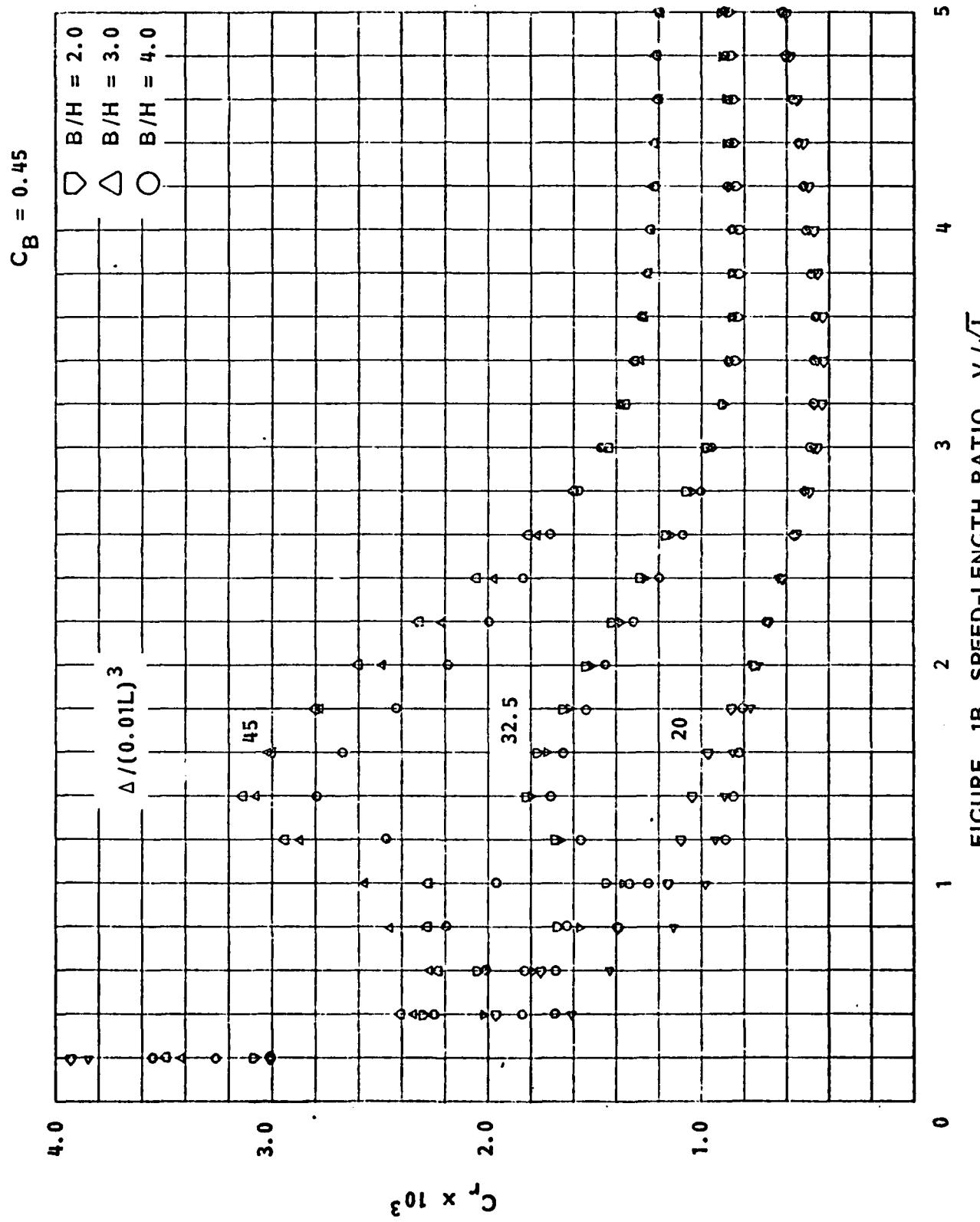


FIGURE 1B SPEED-LENGTH RATIO  $V/\sqrt{L}$

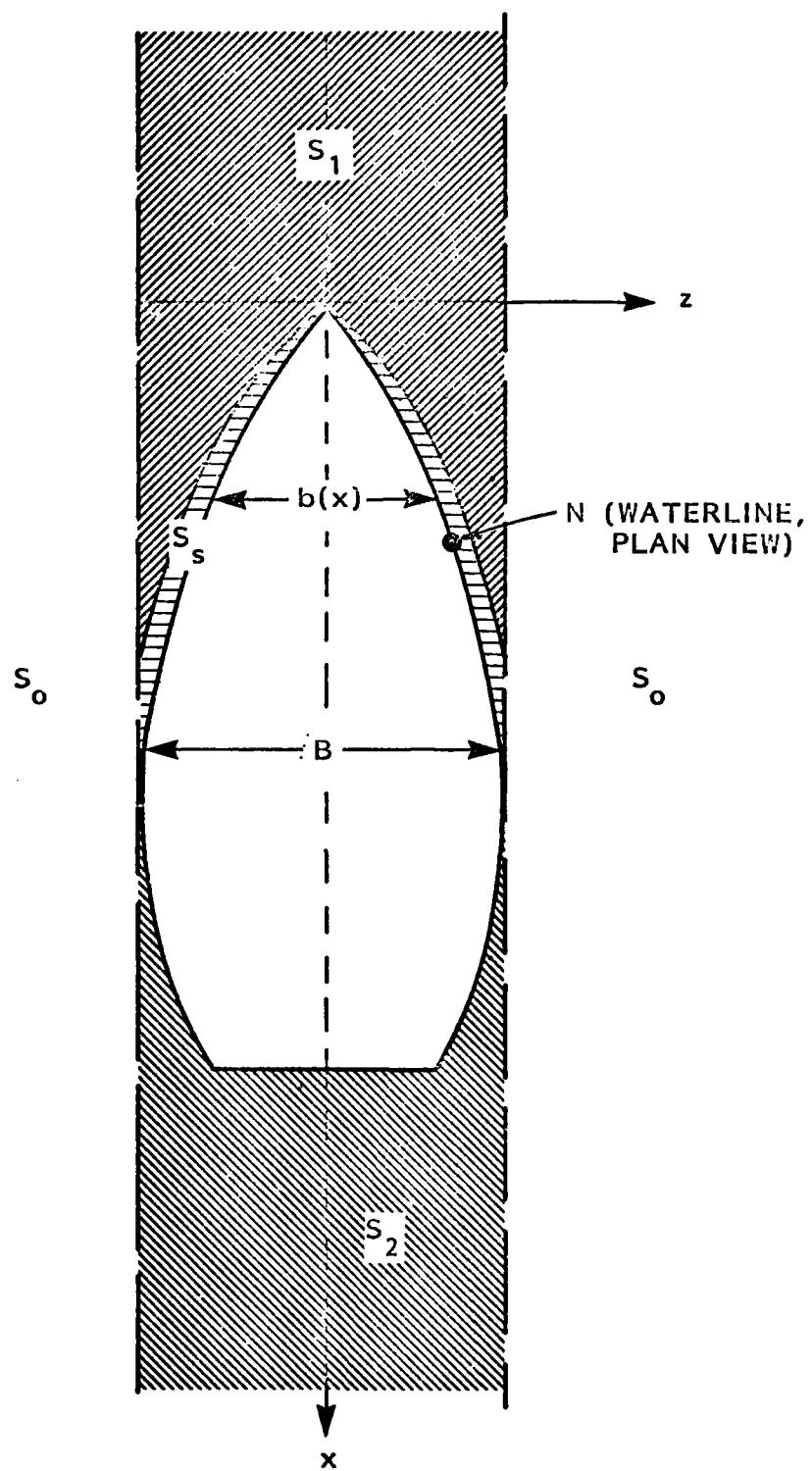


FIGURE 2 - FREE SURFACE REGIONS - HIGH SPEED SHIP

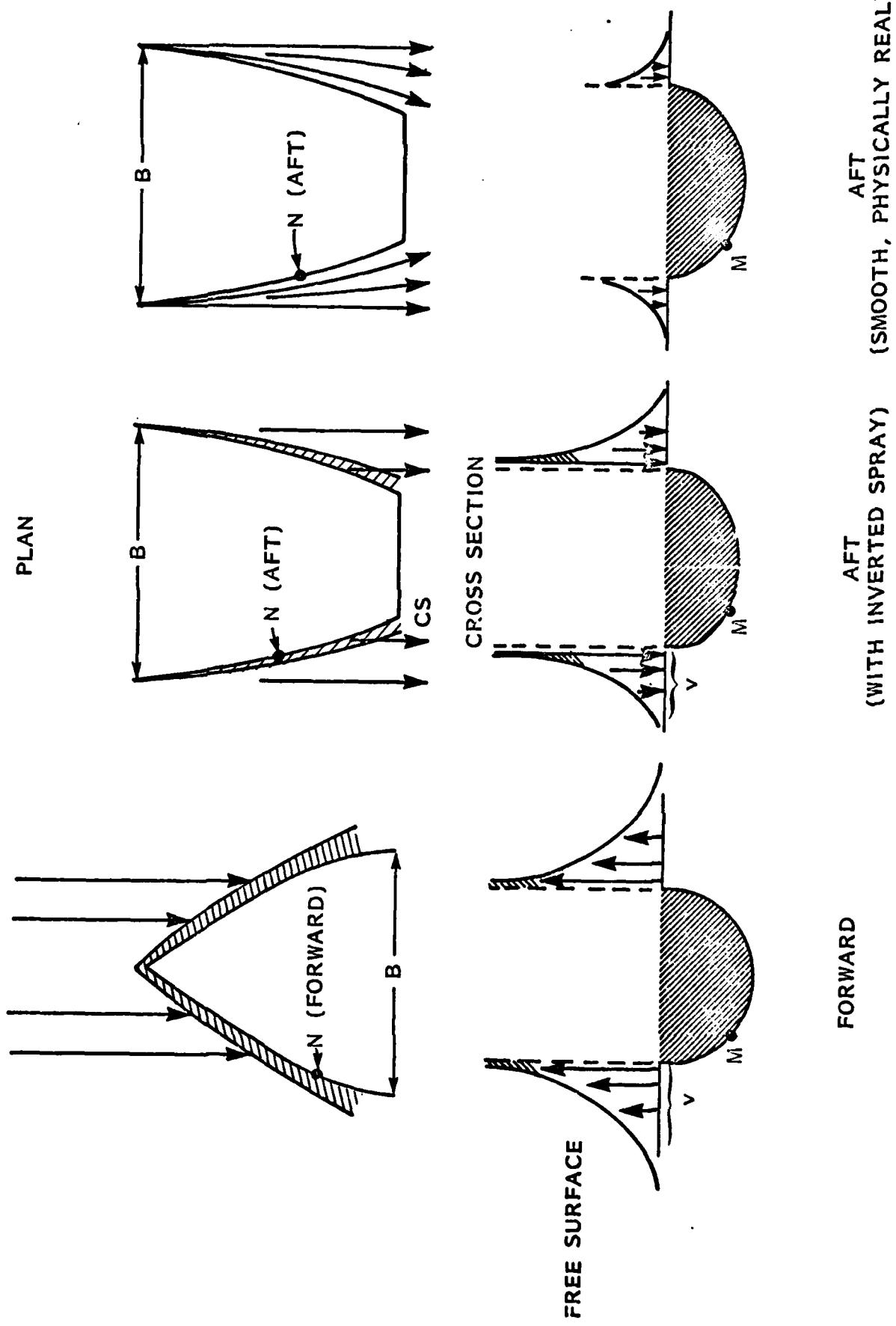


FIGURE 3 - SCHEMATIC OF STREAMLINES AND FREE SURFACE SHAPE

AFT  
(WITH INVERTED SPRAY) (SMOOTH, PHYSICALLY REAL)

FORWARD

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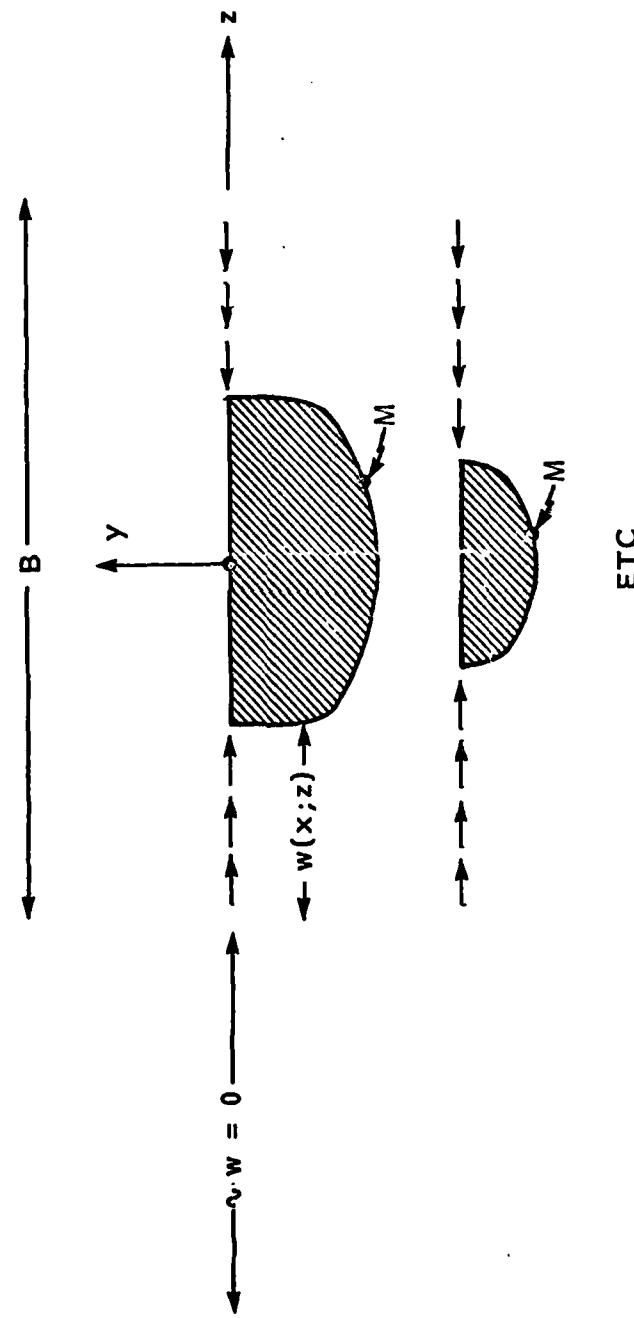
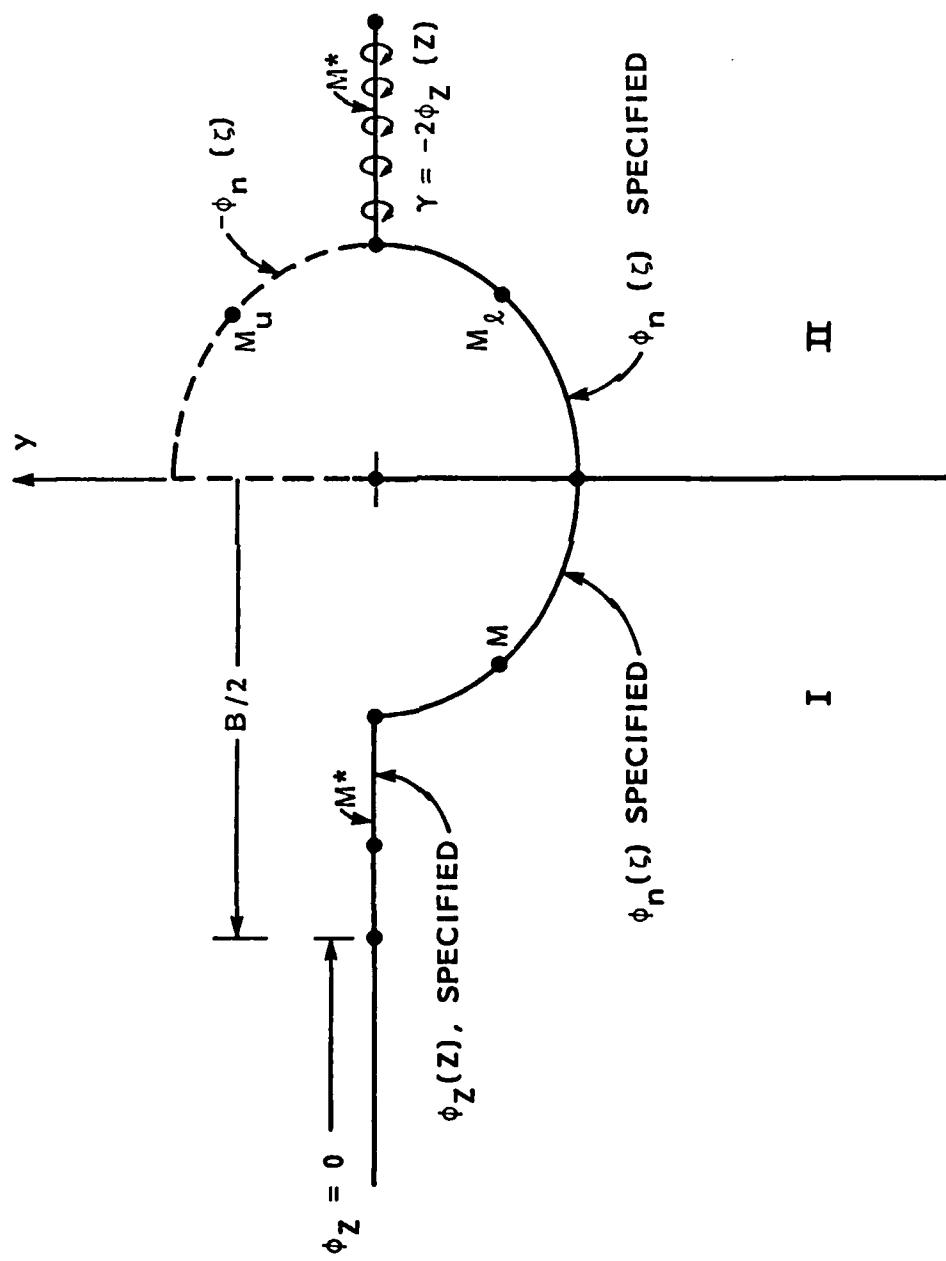


FIGURE 4 - TYPICAL AFT CROSS-SECTIONS SHOWING TRANSVERSE  
VELOCITIES ( $y \geq 0$ ) IN REAR SHADOW OF HULL



THE BOUNDARY VALUE PROBLEMS I & II ARE EQUIVALENT

FIGURE 5 - THE PROBLEM IN THE CROSS-SECTION  
(GIVEN X, AFT)

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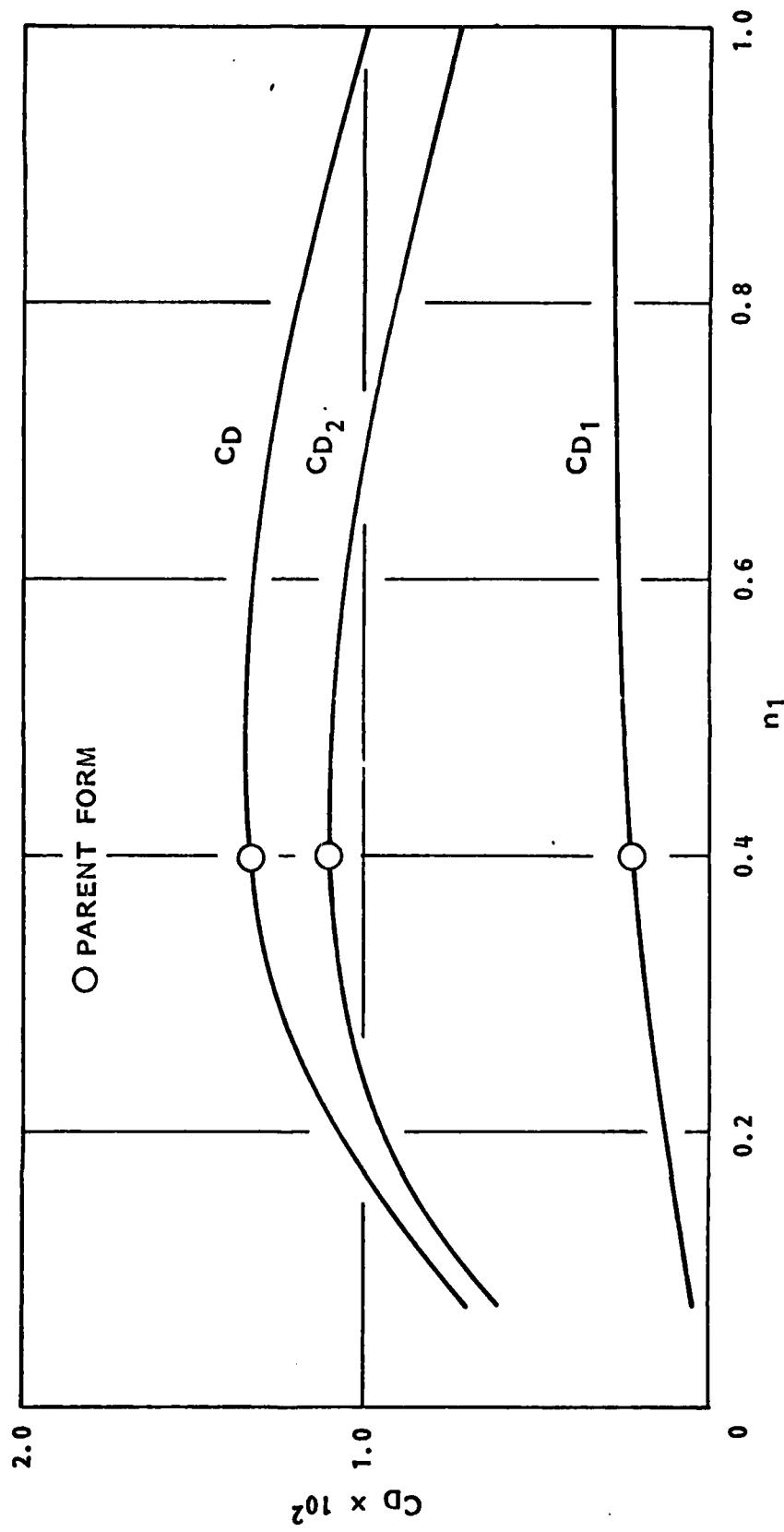


FIGURE 6  $CD$  Vs  $n_1$

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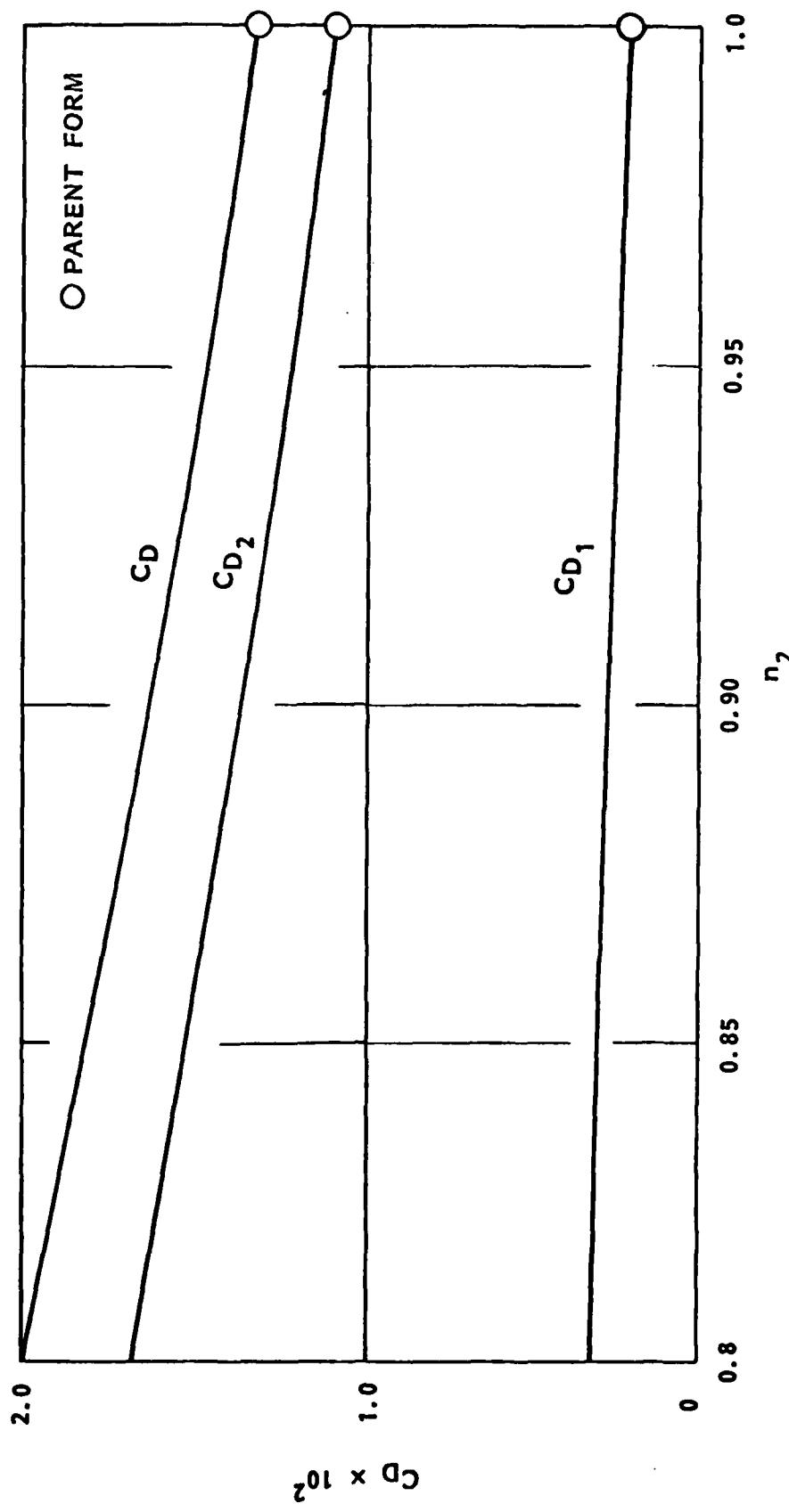


FIGURE ;  $CD$  Vs  $n_2$

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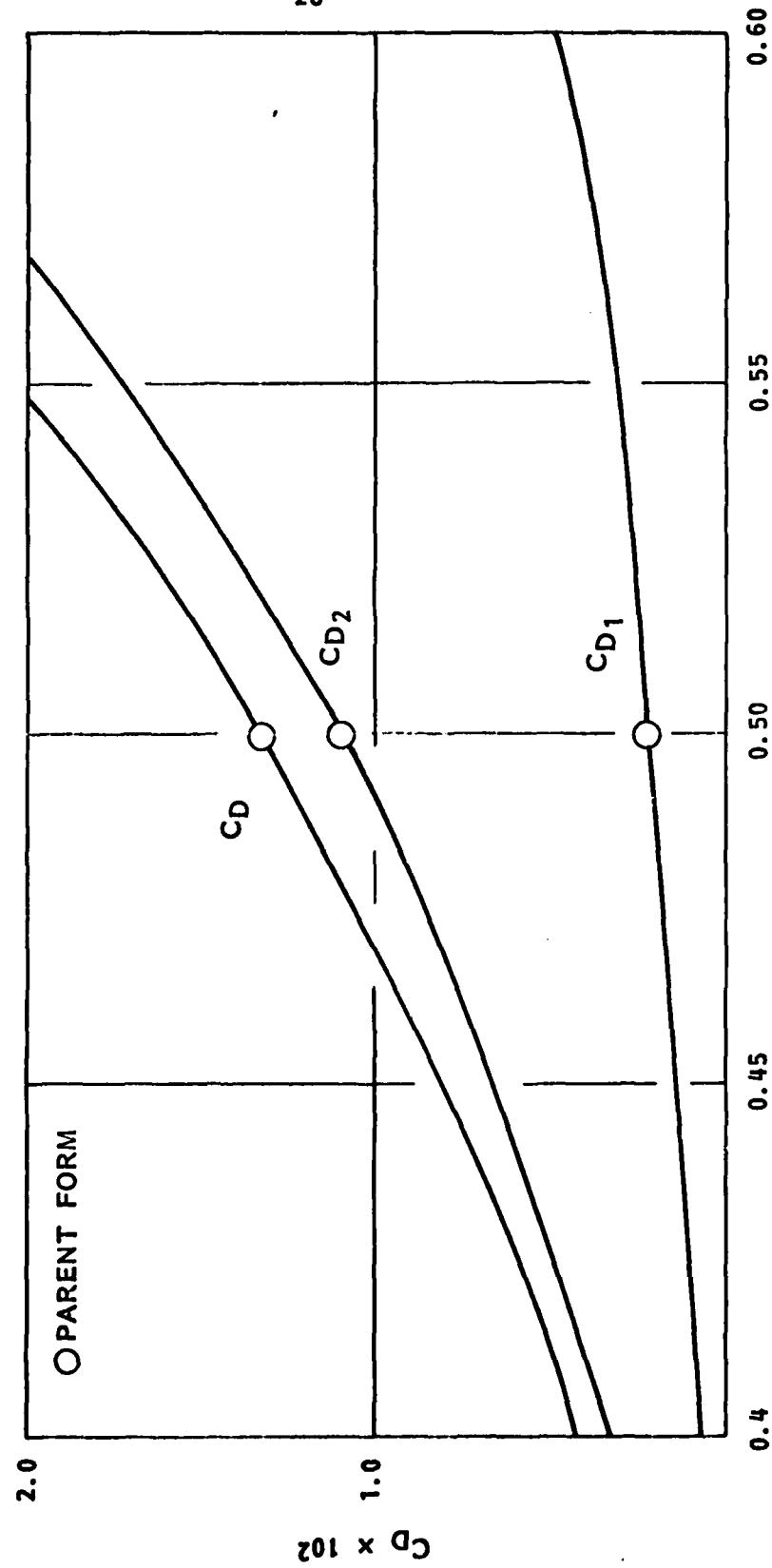


FIGURE 8  $CD$  Vs  $n_3$

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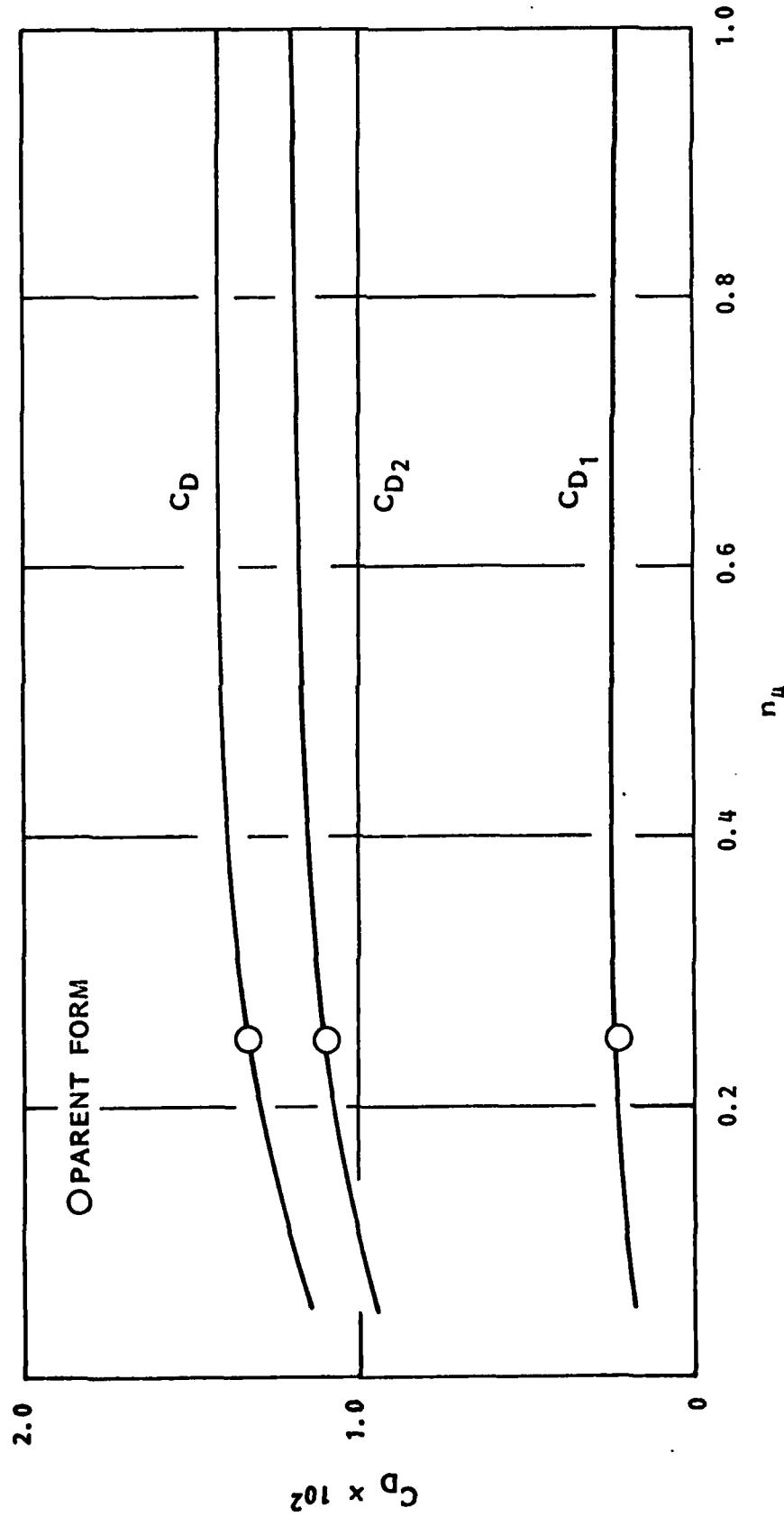


FIGURE 9  $C_D$  Vs  $n_4$

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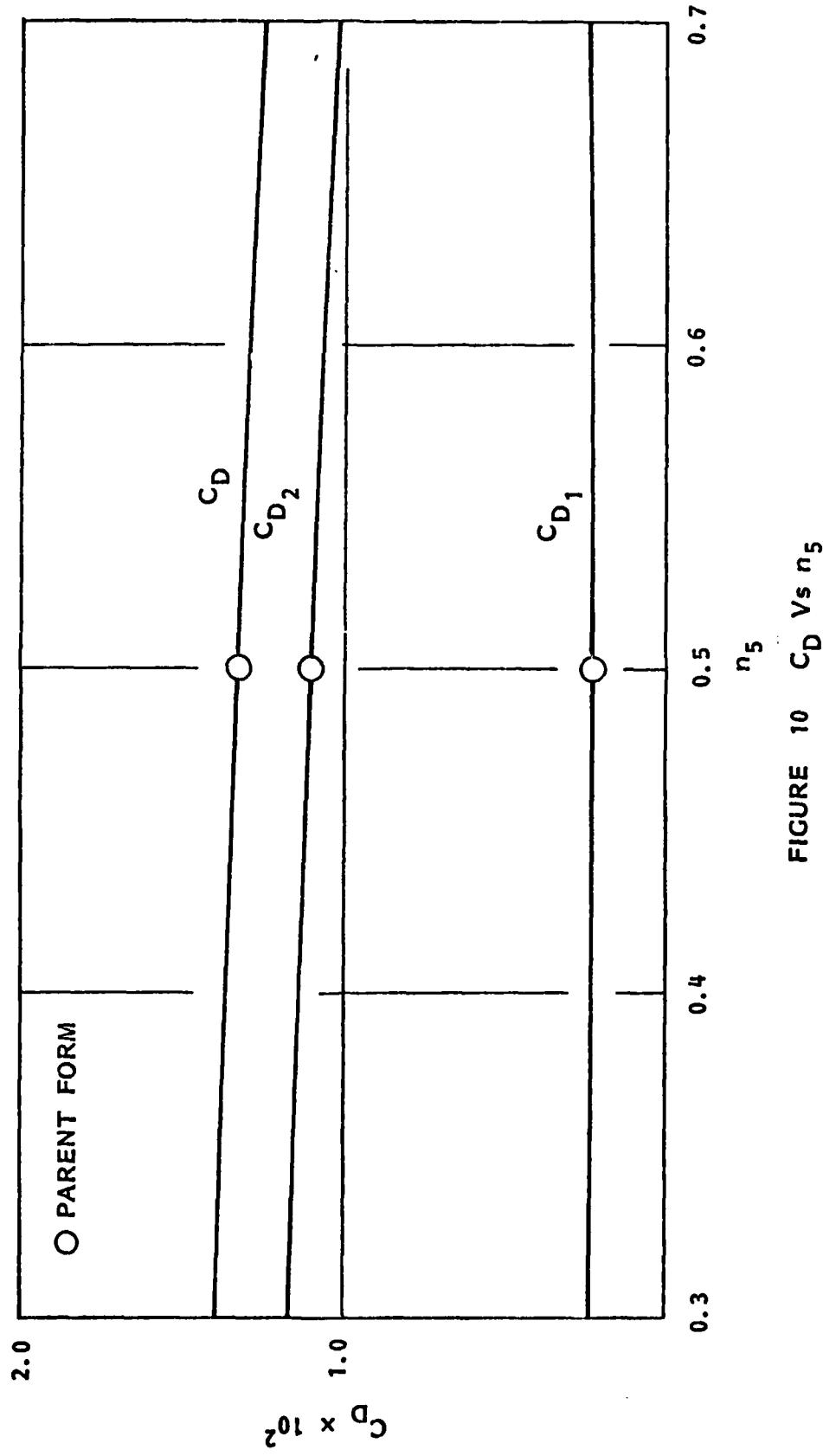


FIGURE 10  $C_D$  Vs  $n_5$

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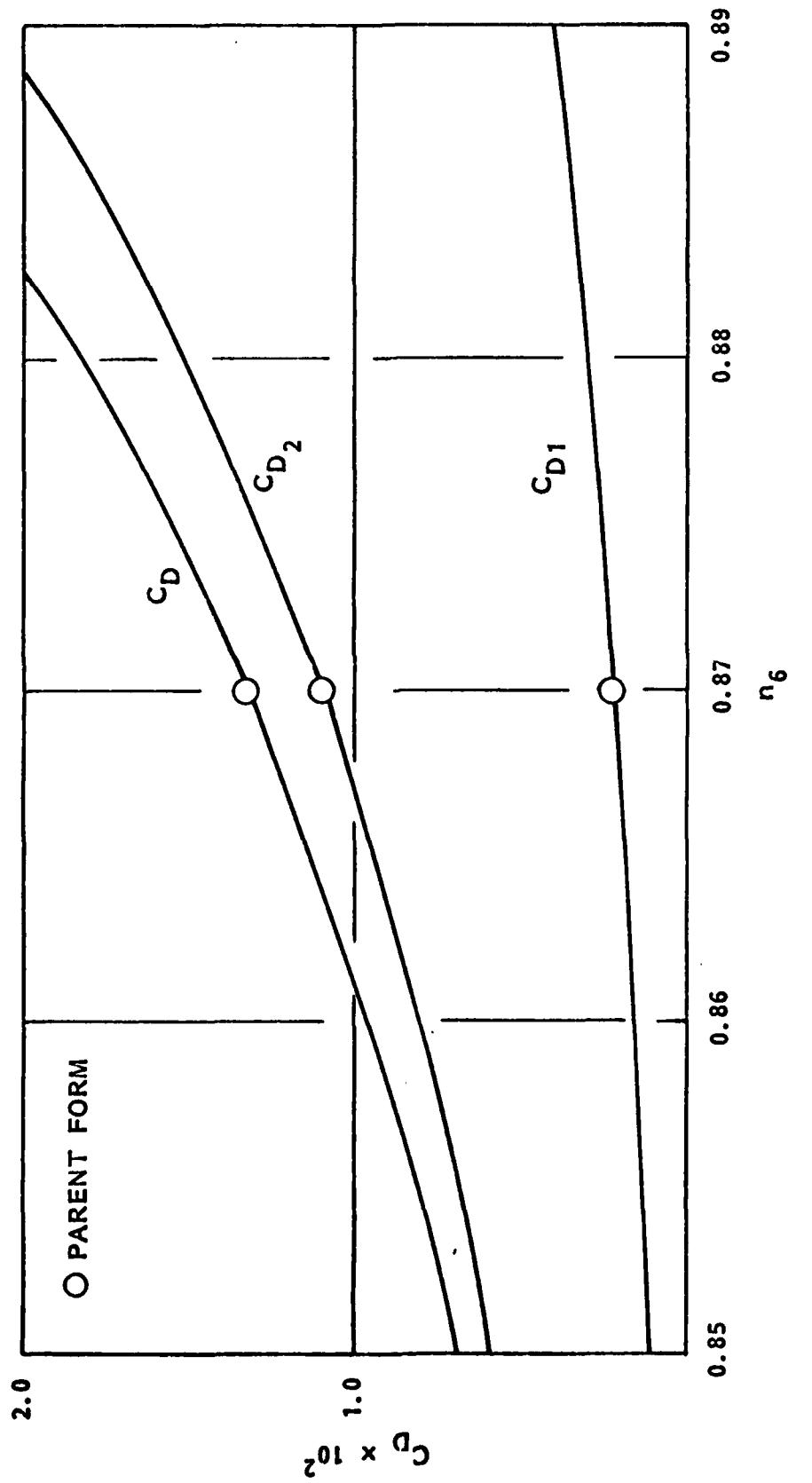


FIGURE 11  $C_D$  Vs  $n_6$

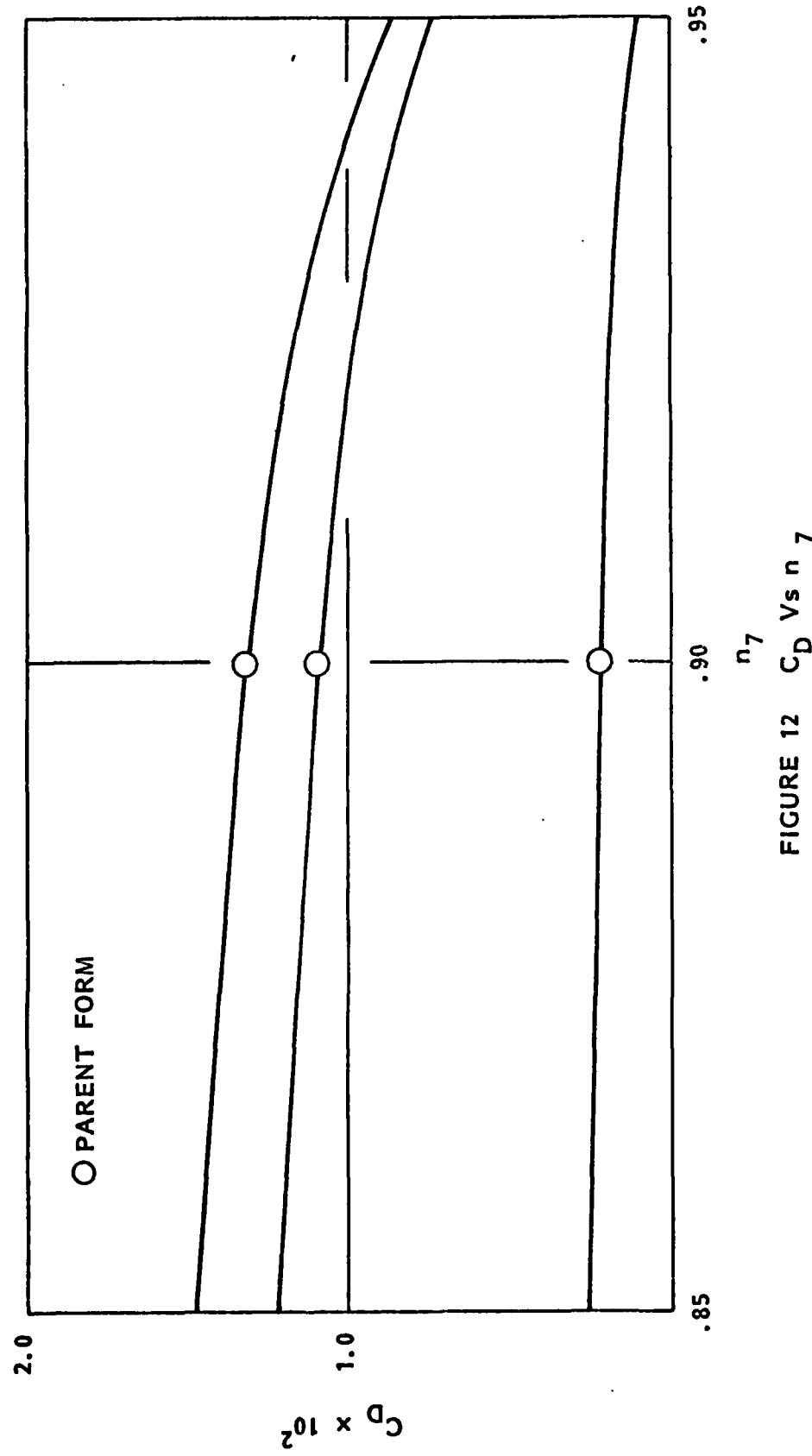


FIGURE 12  $C_D$  Vs  $n_7$

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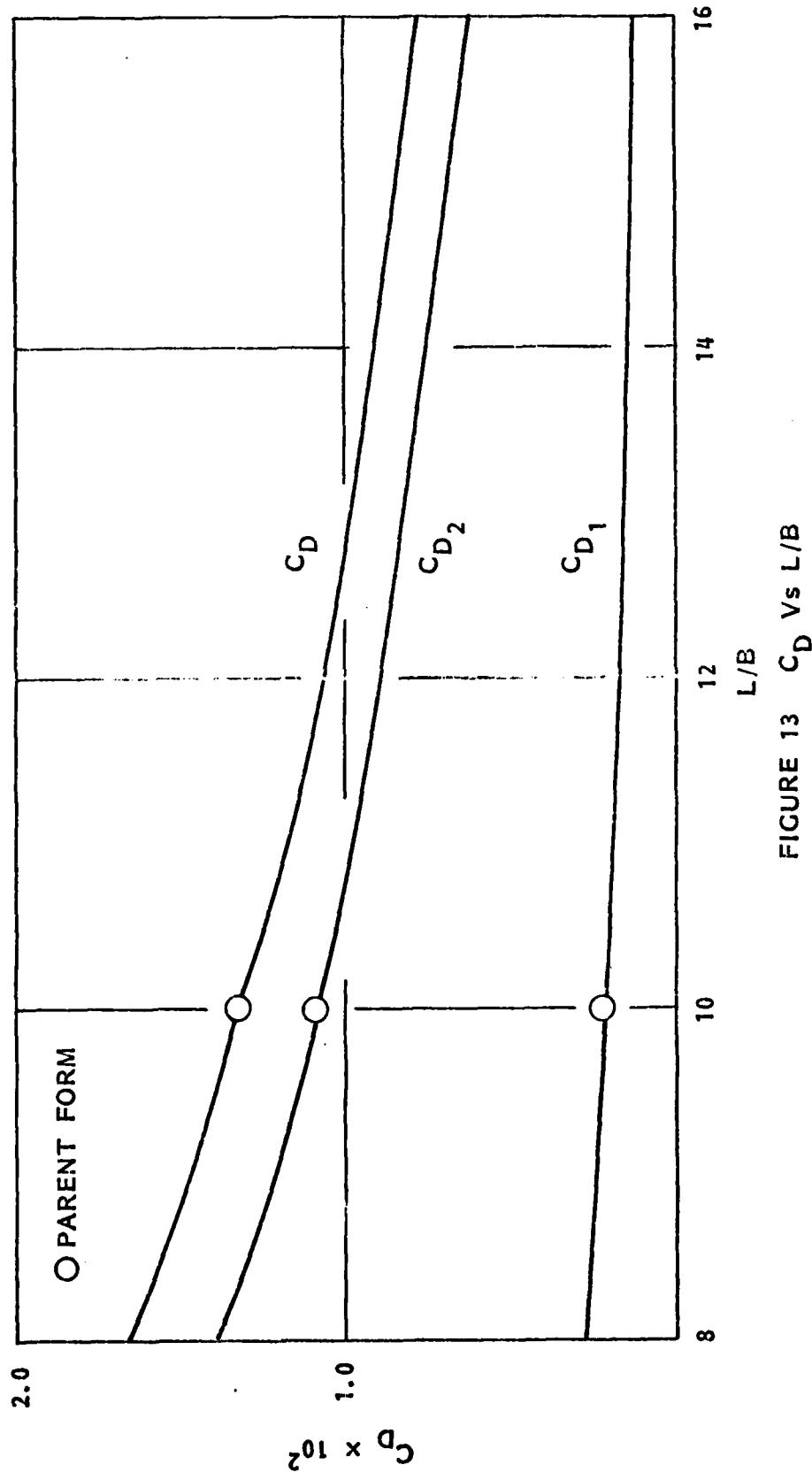


FIGURE 13  $C_D$  Vs  $L/B$

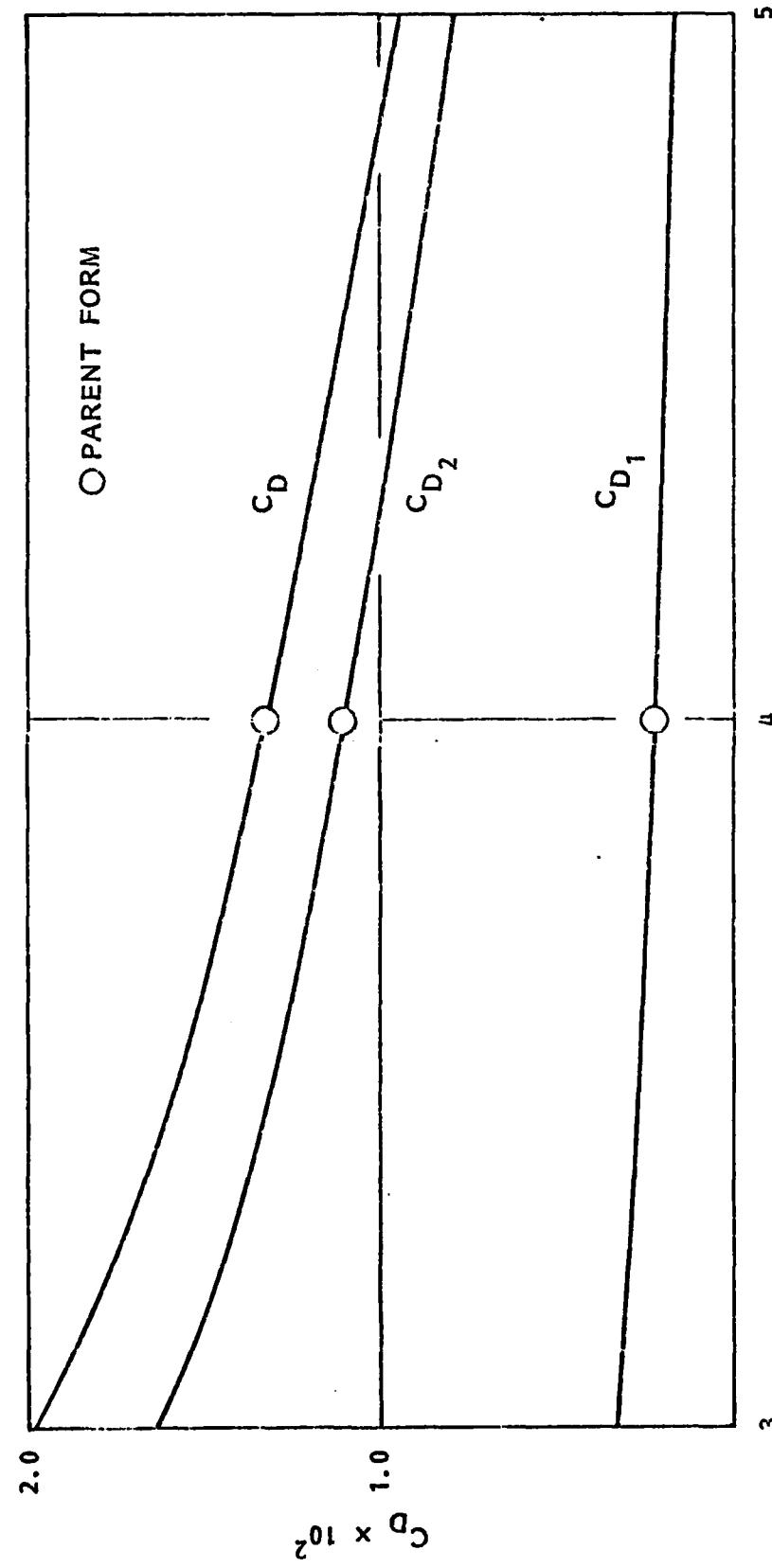


FIGURE 14  $C_D$  Vs  $B/H$

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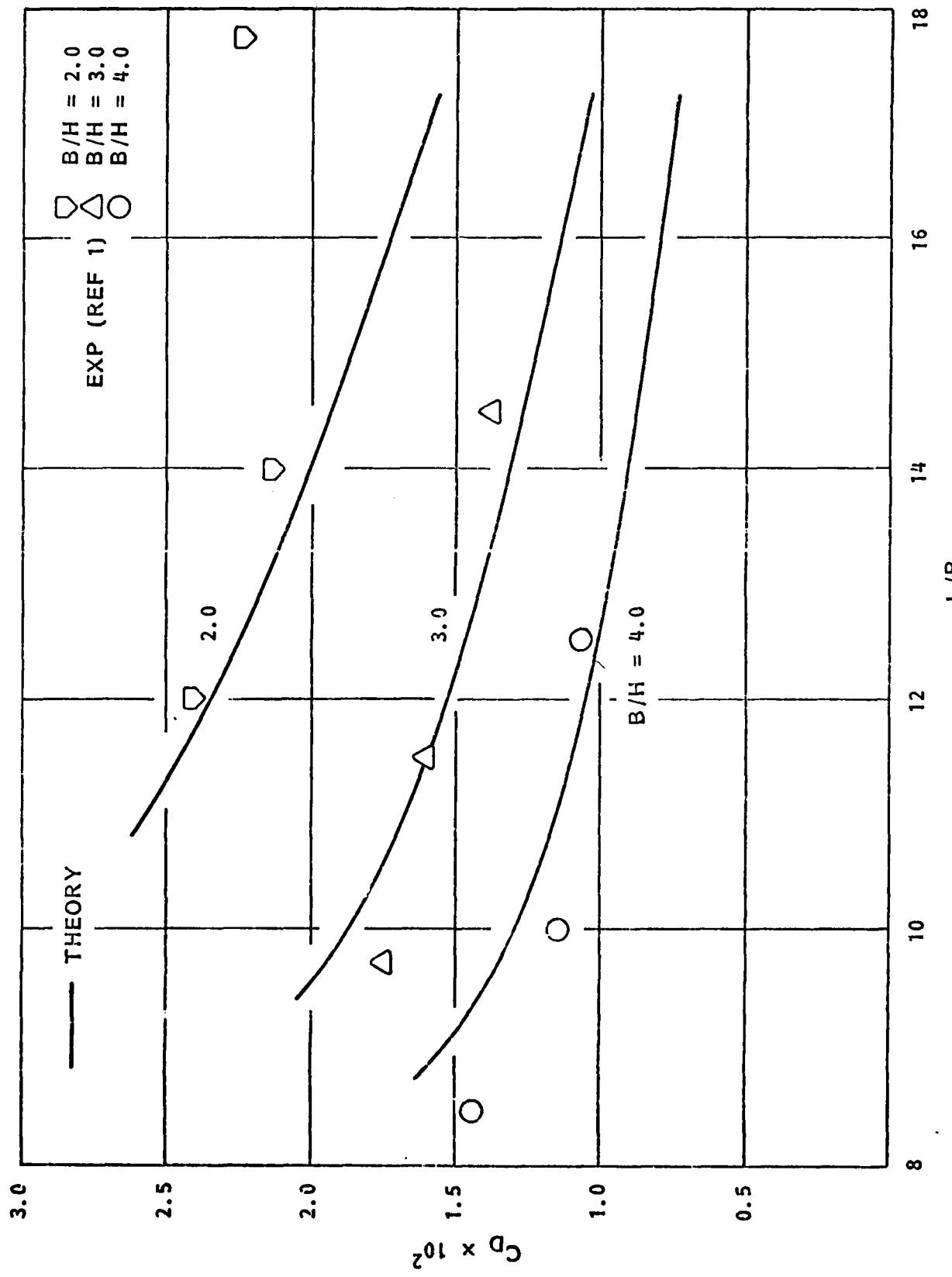


FIGURE 15a COMPARISONS WITH EXPERIMENTS, BLOCK COEFFICIENT = 0.55

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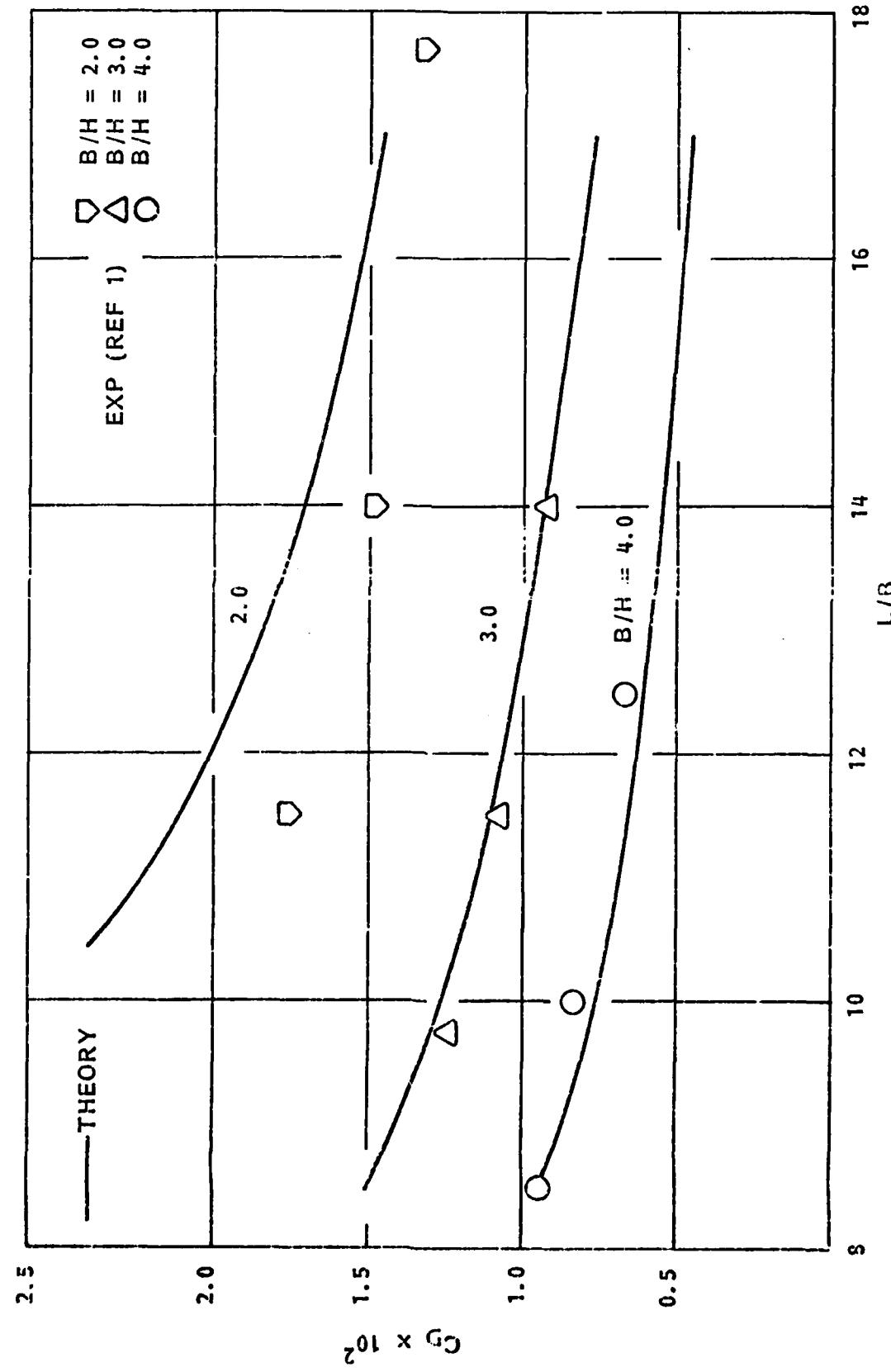


FIGURE 15b CONTINUED, BLOCK COEFFICIENT = 0.15

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